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Thermodynamic and economic feasibility of solar ponds for various thermal applications: A comprehensive review

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ABSTRACT

Solar energy technologies and their applications are as relevant today as they were in 1950s. A comprehensive review of the most recent studies having numerous references to the past research works on the thermodynamic and economic feasibility of solar ponds is presented in this communication. Thermodynamic models for the performance analysis of solar ponds and its validation with the experimental results by a number of researchers are highlighted. Expressions for estimation of energy and exergy efficiencies of all three zones of salt-gradient solar pond are presented. Need of the evaluation and revival of solar pond technology for continuous supply of large quantity of solar thermal energy for low temperature applications has been advocated. Some of these applications are domestic and industrial process heating, heating of building and greenhouse, refrigeration and air-conditioning, desalination and salt production, agriculture and aquaculture, and power generation. Usefulness of the alternative technology of salt-gradient solar ponds such as solar gel ponds, equilibrium solar ponds, and shallow solar ponds has also been incorporated. It has been explored that solar ponds have a great potential of saving a large quantity of energy from degradation as well as exergy destruction due to the use of 'energy based on fossil fuels and electricity' for the purpose of usual low temperature applications. In this way, solar ponds will prove to be helpful in minimizing the present alarming ecological problems and energy shortage by substituting a large fraction of high grade energy consumption.

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1. Introduction

High cost of the solar thermal system is due to lower thermodynamic efficiency, and higher cost of separate solar radiation collection and solar thermal storage systems. It has become essential to build up more economical solar thermal device which can collect as well as store solar energy simultaneously for further applications. Solar pond is a typical example of such solar thermal device among various solar energy systems. The concept of the solar pond is not novel. Research on solar ponds has been conducted in a number of countries. Solar ponds have been successfully built and operated in Europe, USA, Australia and developing countries mostly on an experimental basis and for demonstration purposes in the last 50 years. But the successful technology development process based on energy from fossil fuels and other conventional energy sources accelerated the growth of economy all over the world in 20th century. Less attention towards the commercialization of solar ponds technologies has been paid. Now, time has come to revive the study of solar ponds when there is need of energy supply from non-polluting and renewable energy sources for sustainable development of the world.

It has been established that the solar ponds have all potential with the annual collection efficiency in the range of 15–25 % to perform well for all locations and can supply adequate heat even in regions near the Arctic Circle. The capacity of long term storage which can supply sufficient heat for the entire year is a major attractive characteristic of solar ponds. It has been found that the solar ponds of the area of the order of 1000 m^2 or further are more cost effective than flat plate collector with higher efficiency as their cost per square meter is much less than that of a flat plate collector. It is suitable for space heating, to warm swimming pools and greenhouses, and for a range of industrial processes of low grade heat applications. Applications in the agriculture and rural areas such as crop drying, dairy plants, water desalination and salt production, and power generation using organic fluid Rankine Cycle have proved to be successful. The prospect of solar ponds to power absorption chillers for air-conditioning in hot and humid climates, especially in the Arabian Gulf regions, has also been explored. The concept of combining a salinity gradient solar pond with a chimney to produce power in salt affected areas and other hybrid applications are also being examined [1,2].

A series of useful reviews of the theory and applications of solar ponds have been compiled by Tabor and Weinberger (1981), Nielsen (1988) and Hull et al. (1989) as reported by Duffie and Beckman [2]. Energy analysis of solar ponds have been performed and reported by many researchers. A review on solar ponds by Kaushika [3] covers historical development of solar ponds since 1902, their applications, thermal modeling of salt-gradient solar ponds including analytical and numerical models. Brief economics of solar ponds considered by Wittenberg and Harris (1981) and Sheridan (1982) are also incorporated here. Velmurugan and Srithar [4] have reviewed various designs of solar ponds, prospects to improve performance, factors affecting performance, mode of heat extraction, theoretical simulation, and measurement of parameters, economic analysis and applications. El-Sebaii et al. [5] have reviewed types of solar ponds, energy extraction methods from solar ponds and its some applications.

Recently, performances of solar thermal systems are being studied by researchers on the basis of second law of thermodynamics (i.e. exergy analysis) in addition to energy analysis based on the first law [6–25]. Energy efficiency is not sufficient to evaluate the actual health and overall efficient utilization of energy transfer from and or within any thermodynamic system. Exergy analysis has been found as an effective tool of thermodynamic analysis and optimization. It is felt that the true location and quantity of exergy destruction or irreversibility in the process of solar/solar thermal energy transfer is to be explored. Effective utilization of available solar energy may reduce the size of solar energy collection device reducing the cost of the solar thermal system. At the same time, the energy efficiency and performances of solar thermal systems will also improve.

Review on exergy analysis of solar ponds is scant in the literature. In this communication, the authors have presented a comprehensive review of thermodynamic analysis based on energy as well as exergy. It has also been tried to present the theoretical and experimental studies, utility and economic feasibility of salt-gradient solar ponds for various applications in addition to a brief description of the design and development, principle of working of solar ponds, etc. for further ready reference and research. Brief appraisal of an alternative technology of salt-gradient solar ponds such as solar gel ponds, equilibrium solar ponds, and shallow solar ponds has also been incorporated in the present paper.

2. Design and development of solar ponds

The technology and scientific principles for collection cum storage of solar energy in solar ponds and extraction of heat for various applications and its conversion to electricity are well understood and well documented in scientific papers and books [26]. Types, construction, state-of-the-art of solar ponds, and problems encountered in connection with long-term operation and maintenance are presented briefly in this section of the paper.

2.1. Types, construction and state-of-the-art of solar ponds

An artificially constructed pond in which significant temperature rises are caused to occur in the lower regions by preventing convection is called 'solar pond'. There are mainly four types of solar ponds: salt-gradient solar pond, shallow solar pond, the gel solar pond and the equilibrium solar pond.

2.1.1. Salt-gradient solar ponds

In 1948, Dr. Rudolph Bloch, suggested the concept of a salt-gradient solar pond (SGSP). It is an artificially constructed and relatively shallow (about 1–3 m deep in three layers) body of water in which a stabilizing salinity gradient prevents thermal convection across layers and allows the pond to act as a trap for solar radiation. Salts like Sodium Chloride, Magnesium Chloride or Sodium Nitrate are dissolved in the water with the concentration (C) varying from 20 to 30% at the bottom to almost zero at the top. A simple schematic view of the square shape salt-gradient solar pond is shown in Fig. 1 containing three layers or zones.

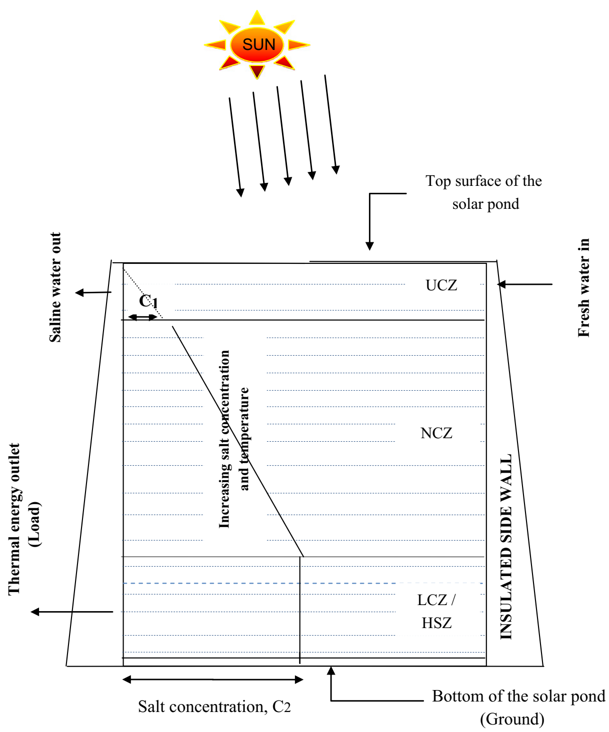

Fig. 1. Cross-sectional diagram of a square shape salt gradient solar pond.

When solar radiation is incident on the solar pond, a part of the radiation is reflected back from the top surface while most of the incident sunlight is transmitted inside through the top surface of the UCZ. The upper convective zone (UCZ) is a thin layer (around 0.10–0.40 m) of nearly salt less water in which there is vertical convection current due to wind and evaporation. The fraction of the transmitted radiation is first rapidly absorbed in the UCZ. However, this absorbed heat is lost to the atmosphere by convection and radiation heat transfer. The remaining radiation is subsequently absorbed in the non-convective zone (NCZ) and heat storage zone (HSZ) before the rest of the radiation reaches the bottom of the pond. The NCZ is much thicker having downward positive salt concentration gradient. Depth of NCZ is more than half of the total depth of the solar pond. The thickness of the NCZ depends on the desired temperature, solar transmission properties and thermal conductance of water. It is an insulating layer reducing the heat losses in the upward direction from the heat storage zone. In the HSZ or lower convective zone (LCZ) or bottom layer, the absorbed solar energy is converted to heat and stored as sensible heat in high concentration brine, where both the salt concentration and the temperature are almost constant. Since there are no heat losses by convection from the bottom layer, the temperature of this layer rises substantially [1–3]. The bottom of the pond is usually lined with a blackened plastic film made of low density polyethylene, high density polyethylene or woven polyester yarn, and hypalon reinforced nylon mesh. It prevents leakage and absorbs maximum solar radiation that reaches the bottom.

The ultimate aim in the design and construction of a solar pond is to extract stored heat for various applications. Heat removal to serve the load take place in the heat storage zone either through a heat exchanger placed in the lower region of the pond or by running the water through a heat exchanger placed nearby. The first method is the most commonly recommended method of extracting heated brine from the HSZ by using an appropriate diffuser to prevent excessive velocities of motion within the pond and thereby minimizing the erosion of the gradient zones. The heat of the heated brine is extracted by an external heat exchanger and the cooled brine is returned to the pond on the other end. The second method involves a heat exchanger that is placed inside the HSZ of the pond. This method of heat extraction has several disadvantages including requirement of large quantity of tubes, difficulties in locating the heat exchanger, repair and maintenance, and corrosion problems, etc. [3,5].

A number of research works are continued to improve the design of the conventional salt-gradient solar ponds to make this technology thermodynamically and economically competitive with the other solar thermal options as well as conventional energy technologies and the same is mentioned at the appropriate place in the present paper.

2.1.2. Solar gel pond

Among other types of the solar ponds, the concept of 'the solar gel pond' is advantageous over a salt-gradient solar pond due to elimination of evaporation losses from the surface with reduction in heat losses. A thick layer of a polymer gel floats on the lower convective zone and acts as the non-convective zone, therefore a salt concentration gradient is not required to be maintained. The polymer gel has a density which is intermediate between fresh water and saline water, thereby enabling it to float on a salt solution. About 2–7% salt solution is used in the lower convective zone to keep the gel layer floating on top. Once a gel that floats on fresh water is developed, the environmental hazard of salt handling is eliminated. The polymer gel has good optical and thermal insulating properties but the cost of the gel is high. At first, an experimental gel pond (18 m^2 surface area and 1.22 m depth) was constructed in the University of New Mexico (UNM) and its schematic is shown in Fig. 2 [27].

Wilkins [28] has given details of the design, construction and operation of two other solar gel ponds. A small commercial scale pond of 110 m^2 area was commissioned in Chambefino, New Mexico and this provided process heat for a food company. Another commercial solar gel pond having area of 400 m^2 and 5 m deep with a gel thickness of 0.60 m had been in operation supplying process heat successfully to a publishing company for about two years in Albuquerque, New Mexico, USA. Tedlar bags were used to contain the gel. During the first year of operation, while the pond was in the process of heating up, the pond obtained a temperature of 60 °C and the gel showed no signs of degradation.

Three different analytical models (Kooi model, Wang and Akbarzadeh model, and Bansal & Kaushik model) are available to simulate the thermal behavior of solar ponds. These models have been slightly modified by Wilkins et al. [29] to represent the gel pond configuration. The optimum thickness of the nonconvective layer (gel) and the thin upper convective layer (fresh water) and

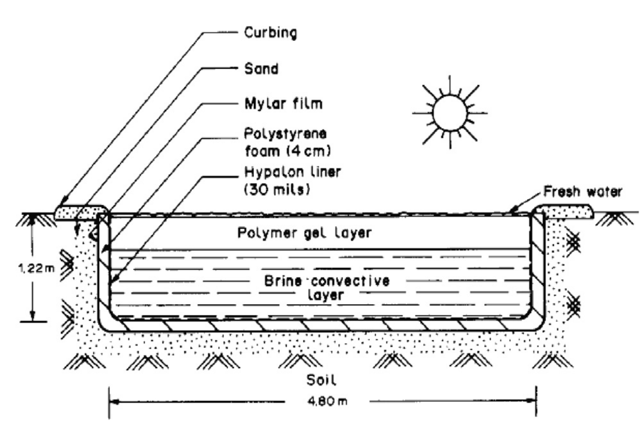

Fig. 2. Schematic of the UNM solar gel pond [27].

their effects on pond performance at a given ambient temperature, insolation and storage temperature have been calculated using all these models. The absorptivity–transmissivity product, a parameter which represents the transparency of the nonconvective and the upper convective layers combined together, has also been estimated. These values have been compared with experimental data as measured through an actual gel layer to test the accuracy of the different models as applied to the gel pond. It is reported that, under the same temperature difference between the storage zone and the ambient (20 °C) and with a yearly average insolation of 250 W/m^2, the model proposed by Wang and Akbarzadeh predicts an efficiency of approximately 32% as compared to the high values of 37.2 and 39% predicted by the Kooi model, and Bansal & Kaushik model, respectively. Under the same conditions, the optimum gel thicknesses predicted by the three models are 0.62, 0.55, and 0.75 m, respectively. It has also been reported that at a given flow rate and thickness of the NCZ, the gel pond has a higher efficiency than the SGSP and solar gel pond shows great promise in the field of the solar pond technology.

A benefit to cost analysis has been performed by El-Housayni and Wilkins [27] on gel ponds with experimental data collected from the circular demonstration gel pond (5 m diameter and 1.25 m depth) located at University of New Mexico. It is observed that solar gel ponds are superior to salt gradient solar ponds from the point of view of efficiency, ease of operation, and economics. They are not yet competitive with conventional fuels for thermal applications, but if the capital costs is reduced (especially the costs of gel and salt), then they can be competitive with conventional fuel costs. The potential and economical feasibility of gel ponds as a source of hot water (45 °C) for domestic use in five regions in the United States have been demonstrated. An industrial applicability of gel ponds as a source of hot water (65 °C) for a textile mill (Cairo, Egypt) has also been shown by considering a case study. In general, it has been observed that for the same size (400 m × 4 m deep), location (southwest) and extraction temperature (45 °C) of solar gel and salt gradient solar ponds, the solar gel pond has higher capital cost (19%), lower operating cost (53%), lower delivered energy cost (26.4%), and higher extraction efficiency (32.5%). While, for the same load output (150 kW thermal) and location (Cairo), a gel pond has higher capital cost (21.5%), lower operating cost (63.5%), smaller surface area (21%), shallower depth (28.6%), and lower delivered energy costs (13%).

2.1.3. Equilibrium solar pond

Two of the major problems in the operation of solar ponds are the establishment and maintenance of the concentration gradient within the insulating layer. To overcome this problem, the saturated salt gradient solar pond was suggested and tested by many scientists. The saturated solar pond is based on salts whose solubility increases with temperature. If enough salt is available within the pond, the temperature gradient produced by the solar radiation will generate a concentration gradient at saturation (or super saturation) conditions. If the dependence of the solubility on temperature is strong enough, the resulting concentration gradient may be large enough so as to produce a stable solar pond. The concept of the equilibrium solar pond is evolved as a generalization of the saturated solar pond, and the anticipated advantages of the former over the latter and over regular solar ponds are reported [30].The need to maintain the salt concentration regularly is eliminated in 'the equilibrium solar pond' by using salts whose solubility in water increases very much with temperature. The details of experimental facilities and techniques are available. The equilibrium solar pond has a major advantage over the saturated solar pond: the fluid in the equilibrium solar pond is unsaturated. This advantage has two important consequences. First, only significant cooling of the fluid in the pond can lead to crystallization, and hence to a reduction in the intensity of light penetration into the pond. This is in contrast with the saturated solar pond, where even the smallest cooling can lead to crystallization. Secondly, the absence of solid salt at the bottom of the equilibrium solar pond as compared with the saturated pond increases significantly the absorption of energy at the pond′s bottom. Therefore, the thermal efficiency of the equilibrium solar pond is expected to be larger than that of the saturated solar pond. A number of salts besides KNO_3 used in this study are found to be appropriate as solutes in the equilibrium solar pond. Those salts are $Na_2B_4O_7$ (borax), $KAl(SO_4)_2$, $CaCl_2$, $MgCl_2$, and NH_4NO_3.

As compared with regular salt gradient solar ponds, the equilibrium solar pond (as well as the saturated solar pond) has the following important advantages:

The zero salt flux throughout the pond eliminates the need for makeup of salt after the pond is set up and the need of disposal of water from the pond.

Due to the high concentration at the bottom region, associated with the equilibrium solar pond (and the saturated solar pond), a higher bottom temperature can be achieved before the onset of boiling of the salt solution, thus increasing the thermal efficiency of the pond.

2.1.4. Shallow solar pond

In addition to 'solar gel pond' and 'equilibrium solar pond', shallow solar ponds (SSP) have been developed and utilized. Unlike classical solar ponds, there is no need of salt gradient layers in SSP. It is essentially a solar energy collection system without long thermal energy storage capacity. Shallow solar ponds are capable of supplying large quantity of heat at cheaper cost with minimum requirement of maintenance and its simplicity in working compared to solar collectors used as water or air heaters for similar purposes. The term SSP has much been derived from that of the solar still. The name implies that the depth of water in the SSP is relatively small, typically 0.04–0.15 m, which is like a conventional solar still consisting of a blackened tray holding some water in it. The still takes advantage of evaporation of salt water by solar heat. In the SSP, a shallow depth of water is covered by means of a plastic film, in such a way that the film is in contact with the top surface of water, and thus prevents the cooling effect due to evaporation [31].

The Solar Energy Group at the Lawrence Livermore Laboratory (LLL), California has developed shallow solar ponds to supply solar heated water between temperatures 25 °C and 60 °C for industrial and commercial uses in around 1973 [32]. It is made of long plastic bag (~5 m × 60 m) filled with water to a depth of very small, typically only a few millimeters (~100 mm). The bag rests on a layer of insulation and is covered with a fiberglass greenhouse glazing material. The bag is filled with water in the morning and allowed to heat up under sunshine. The water reaches its peak temperature in the afternoon. Then it is drained into a separate insulated storage reservoir to provide heat for the rest of the next 24 h period. This module is found to be suitable to heat 30,000L of water from 15 °C to 60 °C under ideal summer conditions in the southwest of the US.

An analytical study of the SSP water heating system consisting of a metallic rectangular tank with black bottom and sides and a transparent cover at the top has been done by Sodha et al. [33]. It is concluded that one dimensional thermodynamic analysis is adequate for prediction of the performance of the shallow solar pond water heater. The daily efficiency would increase if water would be continually withdrawn for consumption, thereby reducing the average pond water temperature and the resultant rate of heat loss. Garg et al. [31] have reviewed the works on the shallow

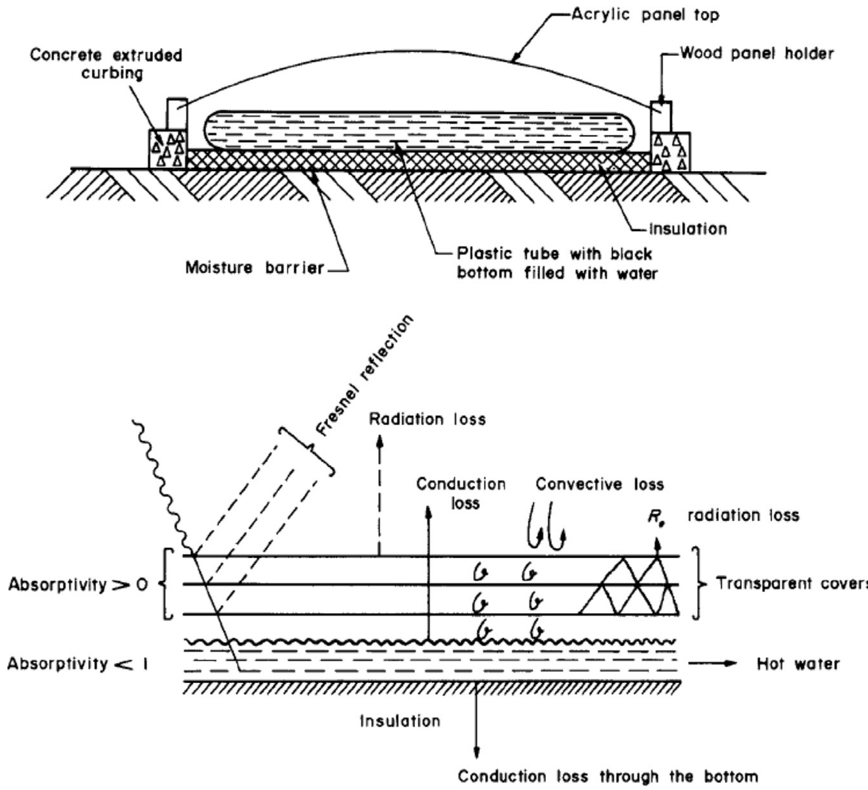

Fig. 3. Schematic and thermal processes of a shallow solar pond [32].

solar ponds in detail. The review also looks into the effects of various parameters, such as the mass flow rate of the liquid, the total mass of water required per day, water depth, radiation intensity, average day-time ambient temperature, number of glazings, total heat loss coefficient, etc. The different modes of flow of the liquid are compared. It is reported that an incorporation of the reflector in the SSP by various workers proved to provide a marked improvement in the system performance. The aspects such as the cost effectiveness, maintenance and reliability of the SSP are briefly presented. A schematic of a SSP is shown in Fig. 3 for an overview.

Erel Company has also developed a shallow water pond in Israel during the late 1980s, thermal diodes composed of an array of translucent honeycombs made of plastic material float on the top of it. The water in the pond was heated up to temperature of about 85 °C. This type of pond is suitable for supplying warm water for household uses and other low temperature applications e.g., laundries, textile factories, canned food factories, greenhouses and the like. A pilot system was installed in Kibbutz Maoz-Haim in Israel to supply hot water for a housing project with 42 units [34].

Recently, some researchers have tried to study the performance of SSP with the aim to improve the design and energy efficiency. A shallow solar-pond integrated with a baffle plate is investigated theoretically and experimentally by El-Sebaii [35] under prevailing weather conditions at Tanta (Egypt). It is found that the present system could provide 88 L of hot water at a maximum temperature of 71 °C at 3:00 pm with a daily efficiency of 64.3% when the baffle plate is used without vents. The pond can retain hot water until 7:00 am of the next day at a temperature of 43 °C, which can be used for most domestic applications.

Al-Hussaini and Suen [36] have carried out a theoretical analysis of shallow solar ponds as an integral part of a greenhouse in cold climatic conditions. The heat given out by the shallow solar pond is used for heating the greenhouse during the day. The collected heat during the day can also be used efficiently for heating the greenhouse at night. The results suggest that there is a huge potential in using shallow solar ponds in greenhouses to save energy in the months from March to October and, specifically, a 100% saving in the summer between May and September with cheaper capital cost investment. The thermal performance of a SSP as shown in Fig. 4 with continuous heat extraction using the batch or the open cycle continuous flow heating modes for heat extraction have been studied experimentally by Ramadan et al. [37] under different operational conditions. Comparison between the two modes for heat extraction has been performed. The measured temperatures for the pond elements are used for calculating the various internal and external heat transfer coefficients, heat loss coefficients and the rates of energy losses and energy collected. It is found that using an additional glass cover reduces the top and total loss coefficients by 54 and 44%, respectively. Further, the year-round performance of the pond has been investigated by computer simulation for the two modes of heat extraction. It is found that, the SSP can be used as a source of hot water required for domestic and industrial applications during most days of the year under prevailing weather conditions of Tanta (Egypt). Under the optimum operational conditions for the batch mode, 88.0 kg of water is obtained at a maximum temperature of about 60 °C at sunset. The same amount of water is obtained at 47 °C at the early morning of the next day which can be used for the most domestic applications. The average values of daily efficiencies, under the batch mode of heat extraction, are obtained as 45 and 32% when the pond is used with single and double glass covers without the outer mirror. However, daily efficiency has the values of 34 and 29% when the pond is used with single and double glass covers with the outer mirror. Daily efficiency of the pond is found to be 38% when it is operated under the open cycle mode of heat extraction.

In order to enhance the productivity of single basin solar stills especially during the night, a shallow solar pond (SSP) was coupled to the still by El-Sebaii et al. [38]. The system consists of

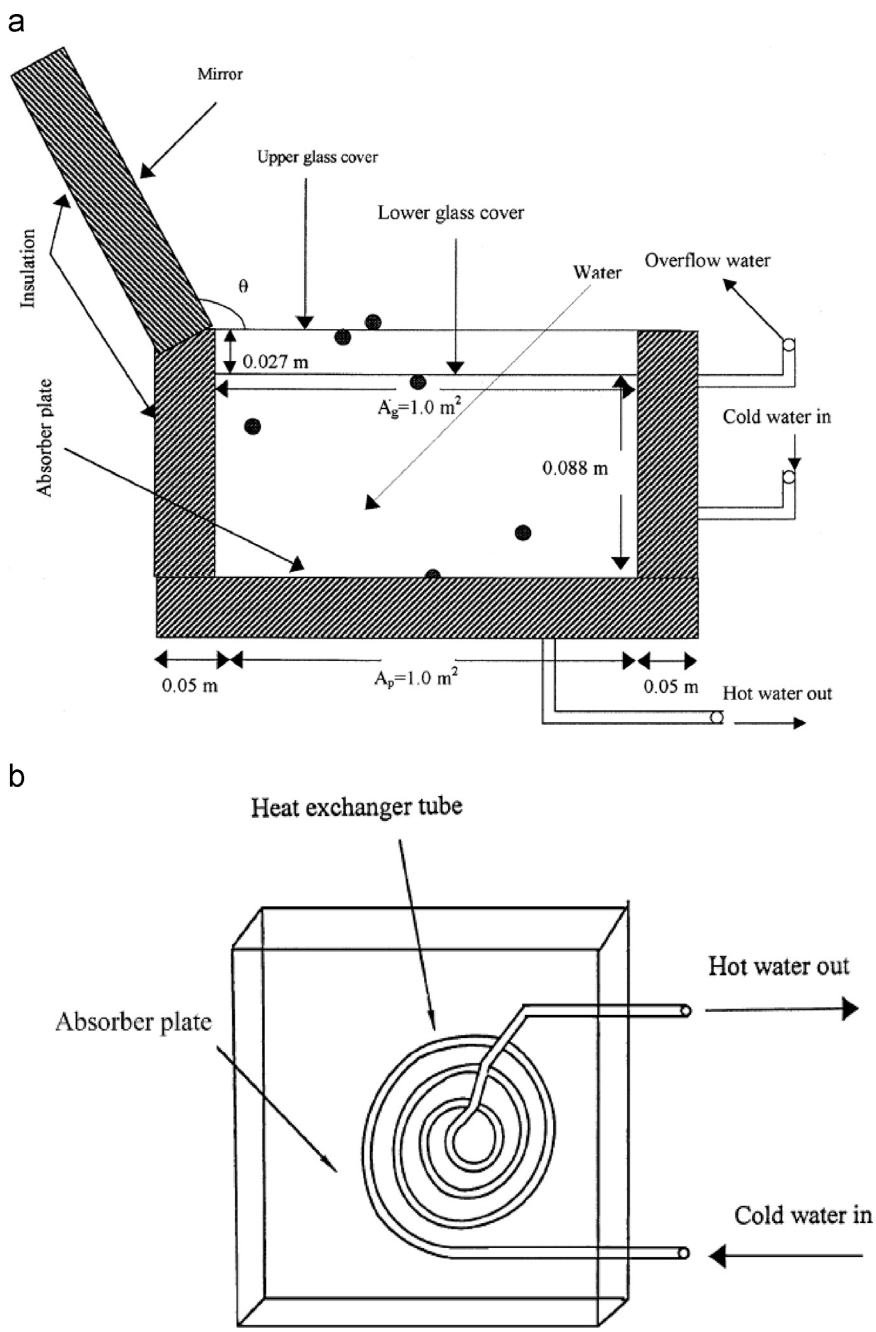

Fig. 4. (a) Schematic of the SSP showing thermocouples positions by black dots and (b) the SSP with a serpentine 'Heat Exchanger' welded to the pond's absorber plate [37].

a single basin solar still operating under the active mode by coupling the still to a shallow solar pond (SSP) is as shown in Fig. 5. The energy balance equations for the various components of the active single basin solar still (ASBS), i.e. basin liner, elemental water length and glass cover are presented in the thermodynamic model. The solution of the energy balance equations for different parts of the active solar still, shallow solar pond and the storage water tank has been obtained with the help of computer program. Input parameters and other details are given. The daily productivities of the ASBS were found to be 5.740 and 1.830 (kg/m^2 day) with and without the SSP, respectively. The daily productivity and efficiency of the active still were found to decrease with increasing the thickness and mass flow rate of the water flowing over the basin liner of the still up to typical values of 0.030 m and 0.015 kg/s. Moreover, the monthly average of the daily productivity had minimum values of 3.0 and 1.570 kg/m^2 day in December, with and without the SSP, respectively. The maximum values were found to be 6.68 and 5.29 kg/m^2 day in July, with and without the SSP, respectively. The daily efficiency of the ASBS with the SSP is higher than that obtained without the SSP by 54.98%. It has been concluded that the considered ASBS offers a suitable solution to the fresh water problems faced by the people living in remote and rural areas in the world especially in developing countries.

2.2. Problems during long-term operation and maintenance of solar ponds

The most important task is to maintain the required salt gradient in all three zones of the solar pond for successful operation. A number of investigations have been carried out; methods have been developed and implemented for establishing the salt gradient. These methods include natural diffusion,

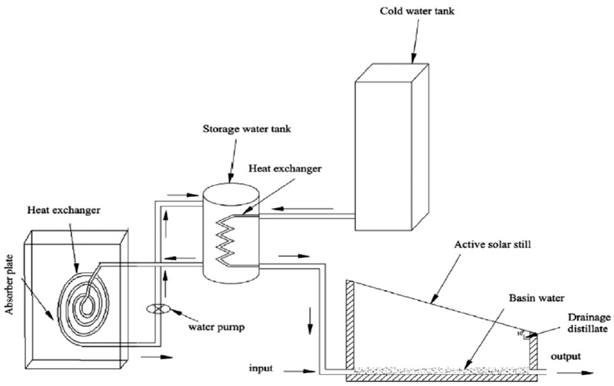

Fig. 5. A schematic of the active solar still coupled with a shallow solar pond and a storage water tank [38].

Fig. 6. A solar pond at RMIT University [39].

stacking, redistribution and falling. Depending on these methods, the solar ponds are also classified as salt gradient solar ponds, partitioned solar ponds, viscosity stabilized solar ponds, membrane stratified solar ponds, saturated solar ponds, membrane viscosity stabilized solar ponds, etc. [3,5]. The impact of other factors like the effect of wind-induced waves and rain, the decreasing transmissivity of the water by the presence of unsettled dirt or leaves on the top surface of pond, reduction in transmissivity due to growth of algae in almost stagnant water, effect of the reflectivity of the bottom, effect of rain, etc. on the performance of any solar pond have also been studied and some measures to counteract these problems are suggested by researchers.

Brine transparency is an important part of the maintenance of a salt-gradient solar pond as it affects the amount of solar radiation reaching the storage zone and hence has an influence on the thermal performance. Several attempts have been made to maintain the clarity in the 53 m^2 circular experimental solar pond shown in Fig. 6. It was constructed in 1998 at the Renewable Energy Park of the School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University located in Melbourne, Australia. Brine shrimps ('Artemia salina' and 'Artemia fransiscana' species), which swim in the pond feeding on algal populations and detritus – the main sources of turbidity, was used for it. In spite of initial success, the population of brine shrimps decreased gradually to extinction. Recently, two different chemical treatment methods for algae growth prevention are tried at Bundoora solar pond: chlorine and a novel chemical product – copper ethylamine complex by Gasulla et al. [39].Cupricide (a copper-based algaecide combining the copper ions with organic complexing agents known as ethanol amines), used first time in a working pond, is more effective than chlorine and is therefore recommended chemical for algae control in solar ponds; it improves the water transparency especially in the UCZ and LCZ with all measurement values less than 1 NTU (nephelometric turbidity units). Chlorine was found to be more corrosive than Cupricide due to its acidic effect on the pH. The preliminary cost analysis showed that granular chlorine is the cheapest chemical.

Sometimes water in the HSZ of solar ponds may be heated over 100 °C in the most favorable conditions, and then there is requirement of managing the rate of heat extraction so that the solar pond does not boil, disrupt salt gradient layers and loses heat. A number of studies referred in the subsequent section of this paper have also shown improvement in the thermal efficiency of the solar ponds by different novel methods and management of the heat extraction.

3. Thermodynamic analysis for performance investigation of solar ponds

To understand the thermal performance of the solar pond, the rates of the absorption of the incident solar radiation and heat transfers in the three zones are to be determined. Estimation or determination of temperatures at various locations inside and outside of solar pond is the most important task for any investigator. Thermodynamic models were developed and validated with the experimental results earlier by a number of pioneer researchers [40–56]. These models were used for the performance analysis of solar ponds through energy analysis based on the first law of thermodynamics. These works are required to be considered again for the evaluation and revival of the solar pond technology based on the second law of thermodynamics, i.e. through exergy analysis.

Exergy analysis has been found as an effective tool to design a more efficient energy system by reducing the irreversibility and inefficiency in the system as well as processes, in addition to the energy analysis. Therefore, it has become necessary to analyze the performance of solar pond through both energy and exergy analyses to achieve better efficiency and effectiveness of the system/processes. The energy and exergy analyses are complementary thermodynamic tools. They are based on the two laws, i.e. first and second laws of thermodynamics.

3.1. First law of thermodynamic analysis: energy model

Energy analysis takes care of the conservation of energy principle. It accounts energy in quantity. It ignores the qualitative aspects of energy [18].

The energy efficiency of any thermal system is defined as the ratio of net energy transfer to the energy input to the system [13] and the same may be applied to the solar pond system, i.e.

$$\eta_e = \frac{Q_{net}}{Q_{in}} \tag{1}$$

The expressions of first law efficiencies (i.e. energy or thermal efficiencies) of the three zones of salt-gradient solar pond are derived and reported by Karakilcik et al. [55] in the form of design and operational parameters. The schematics of the energy flow in UCZ, NCZ and HSZ of an insulated salt-gradient solar pond is illustrated in Fig. 7.

Energy balance equation for the UCZ:

The fraction of incident solar radiation absorbed in the UCZ is converted into heat and the heat transfer from NCZ to UCZ is added accounting to heat stored in the UCZ ($Q_{stored,\ UCZ}$ QUOTE). Rest of the fractions of incident solar radiation associated with reflection and transmission from UCZ is not contributing the heating of UCZ. Therefore, energy balance equation for UCZ may

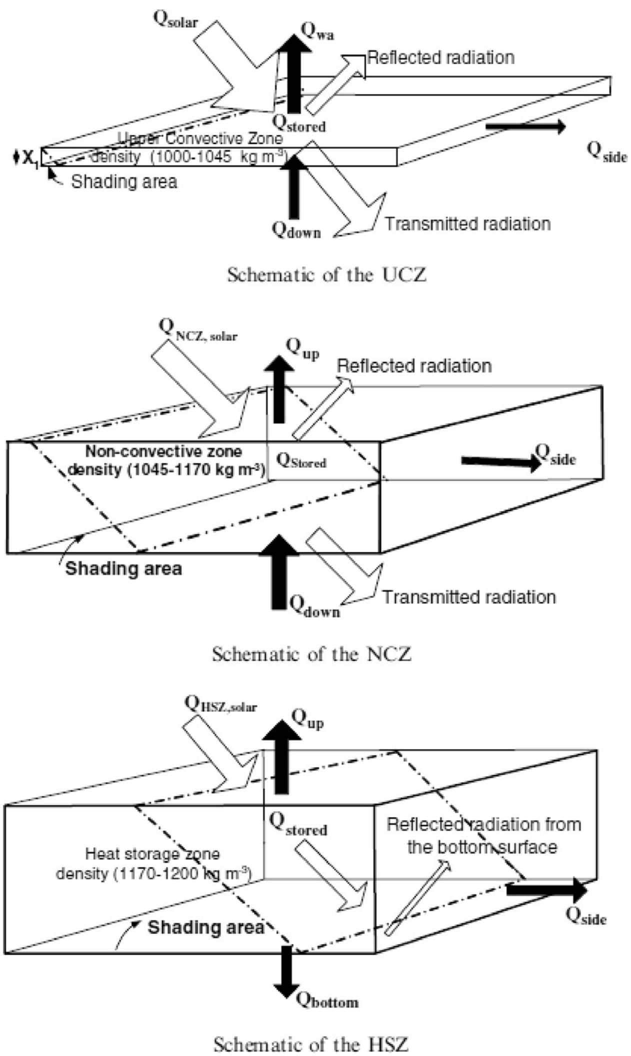

Fig. 7. Schematic of the energy flow in UCZ, NCZ and HSZ of an insulated salt-gradient solar pond [55].

be written as

$$Q_{\text{net, UCZ}} = Q_{\text{stored, UCZ}} = Q_{\text{in}} - Q_{\text{out}} = (Q_{\text{solar absorbed, UCZ}} + Q_{\text{down, from NCZ}}) - (Q_{\text{side, UCZ}} + Q_{\text{wa}}) \tag{2}$$

here, $Q_{\text{net, UCZ}}$ is the net heat transfer through UCZ and it is stored in UCZ i.e. $Q_{\text{stored, UCZ}}$.

The energy (thermal) efficiency of the UCZ is written using Eqs. (1) and (2) i.e.

$$\eta_{e,\text{ UCZ}} = \left[\frac{Q_{\text{net}}}{Q_{\text{in}}}\right]_{\text{UCZ}} = \left[1 - \frac{(Q_{\text{side, UCZ}} + Q_{\text{wa}})}{(Q_{\text{solar absorbed, UCZ}} + Q_{\text{down, from NCZ}})}\right] \tag{3}$$

where, $Q_{\text{side, UCZ}}$ is the total heat loss to the side walls of the pond, Q_{wa} is the total heat lost to the environment from the upper surface of the UCZ, $Q_{\text{solar absorbed, UCZ}}$ is the amount of net incident solar radiation absorbed by the UCZ, and $Q_{\text{down, from NCZ}}$ is the total heat input to UCZ from NCZ on account of heat transfer from non-convection zone.

Energy balance equation for the NCZ:

The fraction of incident solar radiation on UCZ is transmitted into the NCZ. A portion of it is reflected back to the UCZ and another portion is transmitted to the HSZ. Rest of the incident solar radiation is absorbed in the NCZ due to which NCZ is heated and zone's temperature increases. Heat is also added into the NCZ due to heat transfer from HSZ. Therefore, energy balance equation for NCZ may be written as

$$Q_{\text{net, NCZ}} = Q_{\text{stored, NCZ}} = Q_{\text{in}} - Q_{\text{out}} = (Q_{\text{solar absorbed, NCZ}} + Q_{\text{down, from HSZ}}) - (Q_{\text{side, NCZ}} + Q_{\text{up to UCZ}}) \tag{4}$$

The energy (thermal) efficiency of the zone NCZ is written using Eqs. (1) and (4) i.e.

$$\eta_{e,\text{ NCZ}} = \left[\frac{Q_{\text{net}}}{Q_{\text{in}}}\right]_{\text{NCZ}} = \left[1 - \frac{(Q_{\text{side, NCZ}} + Q_{\text{up to UCZ}})}{(Q_{\text{solar absorbed, NCZ}} + Q_{\text{down, from HSZ}})}\right] \tag{5}$$

where, $Q_{\text{up to UCZ}}$ is the heat loss from NCZ to the UCZ, $Q_{\text{solar absorbed, NCZ}}$ is the amount of solar radiation entering the NCZ which is transmitted from the UCZ after attenuation of incident solar radiation in the UCZ, and other terms are analogous to terms used in Eq. (4) with reference to NCZ.

Energy balance equation for the HSZ:

Fraction of the solar radiation incident on the solar pond is transmitted through the UCZ and NCZ, after attenuation, reaches to the HSZ. A part of the transmitted solar radiation from the NCZ to the HSZ is reflected from the bottom and the greater part of the solar radiation is absorbed in the HSZ converting into the stored sensible heat. Hence, the temperature in the HSZ is increased to maximum. Therefore, energy balance equation for HSZ may be written as

$$Q_{\text{net, HSZ}} = Q_{\text{stored, HSZ}} = Q_{\text{in}} - Q_{\text{out}} = Q_{\text{solar absorbed, HSZ}} - (Q_{\text{bottom}} + Q_{\text{side, HSZ}} + Q_{\text{up to NCZ}}) \tag{6}$$

The energy (thermal) efficiency of the HSZ is written using Eqs. (1) and (6) i.e.

$$\eta_{e,\text{ HSZ}} = \left[\frac{Q_{\text{net}}}{Q_{\text{in}}}\right]_{\text{HSZ}} = \left[1 - \frac{(Q_{\text{bottom}} + Q_{\text{side, HSZ}} + Q_{\text{up to NCZ}})}{(Q_{\text{solar absorbed, HSZ}})}\right] \tag{7}$$

where, Q_{bottom} is the heat loss to the bottom from the heat storage zone, and other terms are analogous to terms used in Eq. (5) with reference to HSZ.

3.1.1. *Results of the experimental and theoretical investigation based on energy analysis*

During 1950s, an extensive investigation on small solar ponds has been initiated by Tabor [40]. More than 90 °C temperature was recorded with the collection efficiency of the order of 15% in experimental ponds. The physics of the solar ponds has been presented by Weinberger [41] in detail. The theory outlined in this paper has been validated with the experimental results obtained by many researchers in future publications. An experimental and theoretical investigation of temperature distributions in an insulated solar pond, particularly during daytimes and night times, is presented by Karakilcik et al. [56]. During the months of January, May and August, it is found that the total heat losses from the inner surface of the pond and its bottom and side walls, as a function of temperature difference, are determined to account for 227.76 MJ (e.g., 84.94% from the inner surface, 3.93% from the bottom and 11.13% from the side walls, respectively). Large amount of predicted heat losses between daytimes and night times with the help of developed model present a significant potential for energy savings and storage. Extending this work, Karakilcik et al. [55] have developed a performance model to determine the thermal efficiencies of the pond and its various zones. Temperature difference was seen to be the key driving force in heat transfer, particularly in heat rejection. The highest thermal efficiency was obtained for August as follows: 4.5% for the UCZ, 13.8% for the NCZ and 28.1% for the HSZ, respectively. Fig. 8 shows the efficiencies variations of all three zones of the solar pond with respect to months.

A 50 m^2 circular pond has been constructed by Valderrama et al. [57] in order to evaluate the feasibility of collecting and

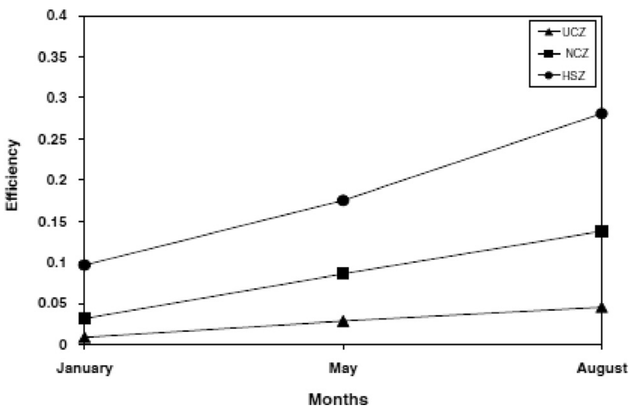

Fig. 8. Variations of efficiencies of all three zones of the solar pond with respect to months [55].

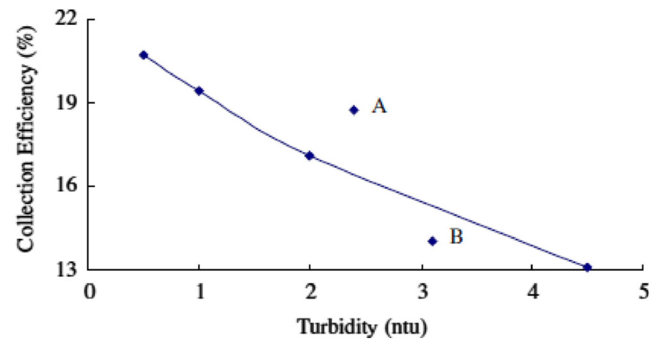

Fig. 9. Variations of solar pond collection efficiency with turbidities [61].

storing solar energy by means of a salinity gradient in order to store heat to be delivered for specific applications. The maximum temperature was observed at the NCZ and then temperature decreased at the LCZ. This fact can be related to the lack of a suitable insulation of the slab which penalizes the heat storage in the bottom. Further, around 10% of total solar radiation along one year is quantified as heat losses to the bottom of the pond, while heat losses to side wall were not significant with less of 0.3% of total solar radiation.

An insulated solar pond with a surface area of 3.5 m^2 and a depth of 1.0 m was built at the University of Jordan to investigate the performance of solar pond under local climate conditions by Sakhrieh and Al-Salaymeh [58]. 16 Thermocouples were used to measure the temperature profile within the pond. The temperature distribution along the solar pond was predicted by developing a computer program and results were compared with the experimental values. A maximum temperature of 47 °C was recorded in the heat storage zone in April 2010.

The shading effects of the side walls are considerable in the case of the thermal analysis of the small solar pond systems. However, it is negligible for large solar ponds. Hassab and El-Masry [59] have examined the collection of solar energy in small solar ponds by including the shading effect of the side walls and illustrated the relative importance. The solar pond storage efficiency can be increased by eliminating the effect of shading area. Karakilcik et al. [60] have presented an experimental investigation of energy distribution, energy efficiency and ratios of the energy efficiency with respect to shading effect on each zones of a small rectangular solar pond. The highest energy efficiencies for the cases of with and without shading area are found to be: 4.22% and 4.30% for the upper convective zone, 13.79% and 16.58% for the non-convective zone, and 28.11% and 37.25% for the lower convective zone, respectively in the month of August. Moreover, the ratios of shading effect are found to be: 0.651 at the lower convective zone, 0.279 at the non-convective zone and 0.068 at the upper convective zone.

A series of experiments were conducted by Li et al. [61] to study the turbidity reduction in solar ponds utilizing seawater as salt source. Thermal performance of a solar pond was simulated in the conditions of different turbidities using a thermal diffusion model. It is observed that the collection efficiency of the solar pond reduces with the increase of turbidity as shown in Fig. 9.

Plastic materials have been used with a great success as liners for small prototypes of solar ponds. However, experience with large solar ponds over 5 km^2 constructed for electricity generation systems shows that if such synthetic liners are used, the cost of the solar pond increases by about 30% as reported by Jubran et al. (1996) referred in the paper written by Silva and Almanza [62]. Other option to use clay liners instead of synthetic materials is investigated. This option reduces the cost of construction and the risk of contamination of subsoil and groundwater by hot brines. In this investigation the following samples are analyzed: native clayey soils with Illite, Montmorillonite and Halloysite, treated and non-treated Bentonites in powder and granulated form, a mixture of Zeolite and Sodium Bentonite, and industrial minerals composed largely of selected clays: Halloysite, Kaolinite and Attapulgite.

3.1.2. Improvement in the performance of solar pond by heat extraction methods

Heat has generally been successfully extracted from the zone LCZ of solar ponds by two main methods; first method: hot brine from the LCZ is circulated through an external heat exchanger, second method: a heat transfer fluid circulates in a closed cycle through an in-pond heat exchanger. Some of the novel methods tried to improve the thermal efficiency of solar ponds by researchers are presented here.

A system of internal heat exchanger was designed for energy removal from the pond by Jaefarzadeh [63]. Fresh water was circulated through an internal heat exchanger, located in the lower convective zone, and transferred its thermal energy to an external heat exchanger. The study covers two periods of summer loading for a week and winter loading for two months. The hourly as well as daily variations of the temperatures of the storage zone, surface zone, ambient, inlet and outlet of the internal heat exchanger have been measured and analyzed. It is shown that the pond may deliver heat with a relatively high thermal efficiency in a transitional stage for a limited period of time. It can also be utilized continuously with a lower efficiency. The efficiency of the small pond in the latter case will be around 10%.

Andrews and Akbarzadeh [64] have explored the possibility of an alternative method of heat extraction from the NCZ, i.e. gradient layer of a solar pond as well as, or instead of, from the LCZ in the theoretical study. It is suggested that the heat extraction from the gradient layer has the potential to increase the overall energy efficiency of a solar pond delivering heat at a relatively high temperature by up to 50%, compared with the conventional method of heat extraction exclusively from the LCZ. The potential gain in efficiency using gradient layer heat extraction is attributed to the lowering of heat losses by conduction to the upper convective (surface) zone that can be achieved with this method. The experimental result of similar novel heat extraction method is presented by Leblanc et al. [65]. An in-pond heat exchanger made of polyethylene pipe has been used to extract heat for over two months. Results indicated the that heat extraction from the gradient layer increases the overall energy efficiency of the solar pond by up to 55%, compared with conventional method of heat extraction solely from the LCZ. From this small-scale experimental study, convection currents are found to be localized only and the

density profiles are unaffected. It is suggested to conduct an experimental study using an external heat exchanger for brine extraction and re-injection at different levels within the gradient layer to determine the effect of the heat extraction from the NCZ on the stability of the salinity gradient (both vertically and horizontally). An economic analysis is required to be conducted to determine the economic gains from increased thermal efficiency.

Tundee et al. [66] have presented the results of experimental and theoretical analysis on the heat extraction process from the LCZ of the solar pond by using the heat pipe heat exchanger (HPHE). In order to conduct research work, a small scale experimental solar pond with an area of 7.0 m^2 and a depth of 1.5 m was built at Khon Kaen in North-Eastern Thailand as shown in Fig. 10. R134a was used as the heat transfer fluid in the experiment. The theoretical model was formulated for the solar pond heat extraction on the basis of the energy conservation equations and by using the solar radiation data for the above location. The modeling equations were solved numerically. In the analysis, the performance of heat exchanger is investigated by varying the velocity of inlet air used to extract heat from the condenser end of the HPHE. Air velocity was found to have a significant influence on the effectiveness of heat pipe heat exchanger. An increase in effectiveness by 43% was investigated as the air velocity decreased from 5 m/s to 1 m/s.

The flat-plate collector has the advantage of converting solar energy into heat very fast compared with solar pond. Without independent heat storage system, collected heat of solar flat-plate collector can be lost, if it is not utilized within a few days. Opposite to this, solar pond (SP) converts solar energy into heat slowly but has a large capacity to store it for long periods. Integrating both the system may balance the opposite characteristics. Improvement in energy efficiency by integrating solar flat-plate collector with solar pond (ISP) through heat exchanger has been assessed recently by Bozkurt et al. [67] by constructing the integrated system Fig. 12 at Space Sciences and Solar Energy Research and Application Center, Cukurova University in Adana, Turkey. The energetic performance of the ISP and SP is studied through energy efficiency analysis and the results SP and ISP are compared for various cases under parametric studies. The energy efficiency profiles for the SP and ISP during a year are shown in Fig. 11. The maximum and minimum efficiencies of the SP and ISP are seen to be obtained in August and January, respectively. For the SP, the efficiency is determined to be an average maximum of 28.41% in August and an average minimum of 8.28% in January. Similarly, the corresponding efficiency for the ISP is observed to be a maximum of 33.55% in August and a minimum of 9.48% in January, respectively. It confirms that the SP storage efficiency can be increased by integrating the system with solar collectors and such ISP systems can be promoted for practical applications.

In another attempt, a solar pond is integrated and constructed with four collectors by Bozkurt and Karakilcik [68] to study the potential of performance improvement and heat storage capability in the solar pond for longer periods. Experiments are performed to determine heat storage, and the efficiencies of the heat storage zone for a particular rate of incident solar radiation and heat energy transferred from solar collectors. The experimental efficiencies are found to be 21.30%, 23.60%, 24.28% and 26.52%; as compared to the theoretical efficiencies: 23.42%, 25.48%, 26.55% and 27.70% , respectively for 1, 2, 3 and 4 collectors.

3.2. Second law of thermodynamic analysis: exergy model

The second law of thermodynamics asserts that exergy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. Exergy analysis is a technique that uses the conservation of mass and conservation

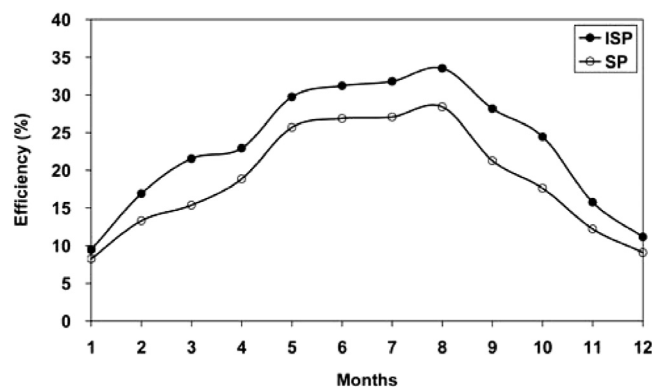

Fig. 11. The energy efficiency profiles for the solar pond (SP) and integrated solar pond (ISP) during a year [67].

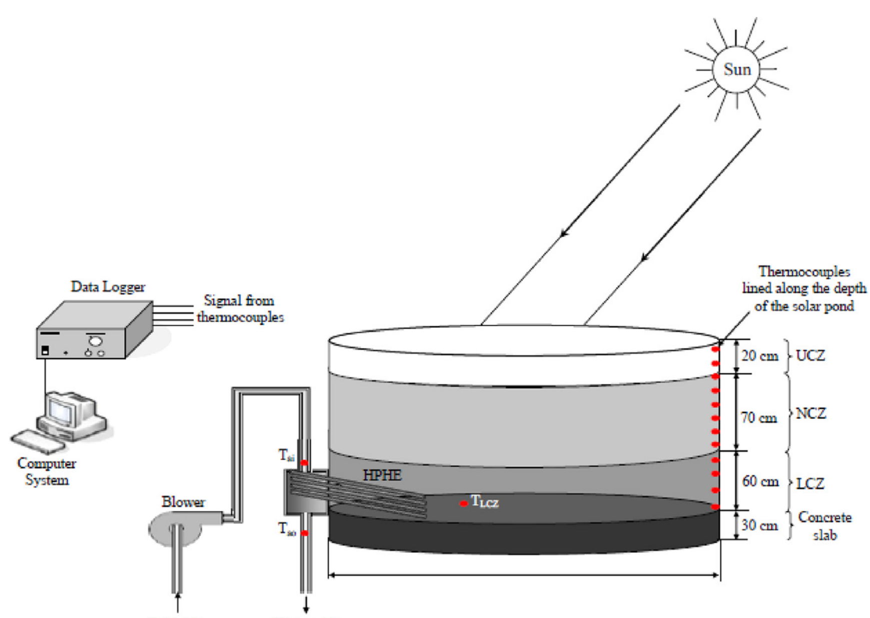

Fig. 10. Experimental setup showing different zones of solar pond, their dimensions, HPHE heat extraction system and associated data acquisition facilities [66].

of energy principles together with the second law of thermodynamics for the analysis, design, optimization and improvement of the energy systems. It indicates the association of exergy losses, i.e. loss of available energy, with heat transfer processes. It allows thermodynamic evaluation of energy conservation in the energy systems because it provides the method for a clear distinction between energy losses to the environment and internal irreversibilities (i.e. exergy destruction) in the processes. Combining the conservation of law of energy and non-conservation law of exergy, a general exergy balance is expressed [14] as

$$\begin{aligned}&\text{Exergy input} - \text{Exergy output (useful and losses)}\\&\quad = \text{Exergy accumulation} + \text{Exergy consumption or destruction}\end{aligned} \tag{8}$$

One of the main objectives of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. A large number of literature exist on exergy analysis of power plants and other engineering applications, but the application of exergy approach to the renewable energy systems, especially on solar ponds may be considered at an early stage.

Exergy analysis may also be a potential thermodynamic tool for design, analysis, evaluation, and performance improvement of solar pond systems. The exergy efficiency or second law of thermodynamic efficiency of a solar pond thermal system or individual zone may be defined as the ratio of desired exergy output, i.e. net exergy transfer (in case of UCZ and NCZ) as useful product or exergy accumulation (in case of heat stored in the HSZ) to the exergy input to the system or individual zone, similar to widely accepted definitions given in literature [13–15], i.e.

$$\eta_{ex} = \frac{E_{X_{out,desired}}}{E_{X_{in}}} \tag{9}$$

The thermal radiation from the sun is relatively rich in exergy [15]. The total incoming solar exergy i.e. exergy of the solar radiation ($E_{X_{solar}}$), on the top surface of solar pond is calculated by multiplying the rate of incident solar radiation, G_s (W/m^2) to the Petela expression (Ψ_s), i.e.

$$\Psi_s = \left[1 + \frac{1}{3}\left(\frac{T_o}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_o}{T_S}\right)\right]$$

and surface area of the solar pond (A). Thus,

Exergy of the solar radiation in watt (W) on the top surface of solar pond is given as

$$E_{X_{solar}} = G_s\left[1 + \frac{1}{3}\left(\frac{T_o}{T_S}\right)^4 - \frac{4}{3}\left(\frac{T_o}{T_S}\right)\right]A \tag{10}$$

where, T_o. is the reference temperature of the environment or temperature of the dead state in Kelvin, and T_S is the sun's surface temperature taken as 6000 K [15].

The exergy (work potential) of heat or rate of exergy transfer accompanying heat connected to internal and external heat transfer of solar pond per unit area may be expressed by a general equation [13]:

$$E_{X_q} = q\left(1 - \frac{T_o}{T}\right) \tag{11}$$

where, q is the rate of heat transfer (W/m^2), T is the temperature of the system in general (Kelvin), but for solar pond, T is the temperature of layers/zones and T_o is the reference temperature of the environment or temperature of the dead state (Kelvin).

In the previous section of energy analysis model, all heat transfers (Q) in W are considered as the heat transfer perpendicular to the cross sectional area of the surface (m^2). Thus Eq. (11) is modified as Eq. (12) and used in the exergy analysis of solar pond as

$$E_{X_Q} = \left[(qA)\left(1 - \frac{T_o}{T}\right)\right] = \left[(Q)\left(1 - \frac{T_o}{T}\right)\right] \tag{12}$$

where, E_{X_Q} is the exergy of heat transfer in W.

The second law efficiencies (i.e. exergy efficiencies) of the three zones of salt-gradient solar pond are derived and expressed by Karakilcik and Dincer [21] based on the exergy balance equations. These expressions are presented in this section with modification in the nomenclature.

Exergy balance equation for the UCZ:

Input exergy to the UCZ = the exergy of solar radiation reaching the UCZ ($E_{X_{solar}}$) + the exergy gained from the NCZ ($E_{X_{Q-g,\ NCZ}}$).
Exergy losses from the UCZ = the exergy loss from UCZ to the environment ($E_{X_{Q-g,\ UCZ}}$) + the exergy loss through side walls of the UCZ ($E_{X_{Q-sw,\ UCZ}}$).
Exergy destruction in the UCZ = $E_{X_{Q-d,\ UCZ}}$.

If exergy accumulation in the UCZ is assumed to be negligible, then the exergy balance equation for the UCZ may be written using Eq. (8) as

$$[E_{X_{out,\ desired}}]_{UCZ} = [(E_{X_{solar}} + E_{X_{Q-g,\ NCZ}}) - (E_{X_{Q-a,\ UCZ}} + E_{X_{Q-sw,\ UCZ}}) - E_{X_{Q-d,\ UCZ}}] \tag{13}$$

The exergy efficiency of the UCZ may be written using Eqs. (9) and (13) as

$$\eta_{ex,\ UCZ} = \left[\frac{E_{X_{out,\ desired}}}{E_{X_{in}}}\right]_{UCZ} = 1 - \frac{[(E_{X_{Q-a,\ UCZ}} + E_{X_{Q-sw,\ UCZ}}) + E_{X_{Q-d,\ UCZ}}]}{(E_{X_{solar}} + E_{X_{Q-g,\ NCZ}})} \tag{14}$$

Exergy balance equation for the NCZ:

Input exergy to the NCZ = the exergy coming from the UCZ to the NCZ, i.e. $(E_{X_{out,\ desired}})_{UCZ}$ + the exergy gained from the HSZ ($E_{X_{Q-g,\ HSZ}}$).
Exergy losses from the NCZ = the exergy loss from NCZ to UCZ ($E_{X_{Q-l,\ NCZ}}$ equivalent to $E_{X_{Q-g,\ NCZ}}$) + the exergy loss through side walls of the NCZ ($E_{X_{Q-sw,\ NCZ}}$).
Exergy destruction in the NCZ = $E_{X_{Q-d,\ NCZ}}$.

If exergy accumulation in the NCZ is assumed to be negligible, then the exergy balance equation for the NCZ may be written using Eq. (8) as

$$\begin{aligned}[E_{X_{out,\ desired}}]_{NCZ} = [&(E_{X_{out,\ desired}})_{UCZ} + E_{X_{Q-g,\ HSZ}}\\&- (E_{X_{Q-l,\ NCZ}} + E_{X_{Q-sw,\ NCZ}}) - E_{X_{Q-d,\ NCZ}}]\end{aligned} \tag{15}$$

The exergy efficiency of the NCZ may be written using Eqs. (9) and (15) as

$$\eta_{ex,\ NCZ} = \left[\frac{E_{X_{out,\ desired}}}{E_{X_{in}}}\right]_{NCZ} = 1 - \frac{[(E_{X_{Q-l,\ NCZ}} + E_{X_{Q-sw,\ NCZ}}) + E_{X_{Q-d,\ NCZ}}]}{\left[(E_{X_{out,\ desired}})_{UCZ} + E_{X_{Q-g,\ HSZ}}\right]} \tag{16}$$

Exergy balance equation for the HSZ:

Input exergy to the HSZ = the exergy coming from the NCZ to the HSZ, i.e. $(E_{X_{out,\ desired}})_{NCZ}$.
Exergy losses from the HSZ = the exergy loss from HSZ to NCZ ($E_{X_{Q-l,\ HSZ}}$ equivalent to $E_{X_{Q-g,\ HSZ}}$) + the exergy loss through side walls of the HSZ ($E_{X_{Q-sw,\ HSZ}}$) + the exergy loss through bottom of HSZ ($E_{X_{Q-b,\ HSZ}}$).
Exergy destruction in the HSZ = $E_{X_{Q-d,\ HSZ}}$.
The exergy accumulation in the HSZ is the desired exergy output of the solar pond in the form of exergy stored in the HSZ, i.e. ($E_{X_{Q-stored,\ HSZ}}$).

Thus, the exergy balance equation for the HSZ may be written using Eq. (8) as

$$[E_{X_{\text{out, desired}}}]_{\text{HSZ}} = [E_{X_{Q-\text{stored, HSZ}}}] = [(E_{X_{\text{out, desired}}})_{\text{NCZ}} - (E_{X_{Q-l,\ \text{HSZ}}} + E_{X_{Q-\text{sw, HSZ}}} + E_{X_{Q-b,\ \text{HSZ}}}) - E_{X_{Q-d,\ \text{HSZ}}}] \quad (17)$$

The exergy efficiency of the HSZ may be written using Eqs. (9) and (17) as

$$\eta_{\text{ex, HSZ}} = \left[\frac{E_{X_{\text{out, desired}}}}{E_{X_{\text{in}}}}\right]_{\text{HSZ}} = 1 - \frac{[(E_{X_{Q-l,\ \text{HSZ}}} + E_{X_{Q-\text{sw, HSZ}}} + E_{X_{Q-b,\ \text{HSZ}}}) + E_{X_{Q-d,\ \text{HSZ}}}]}{[(E_{X_{\text{out, desired}}})_{\text{NCZ}}]} \quad (18)$$

3.2.1. Results of the experimental and theoretical investigation based on exergy analysis

An experimental and theoretical investigation of the exergetic performance of a salt gradient solar pond with a surface area of $2 \times 2\ \text{m}^2$ and depth of 1.5 m has been done by Karakilcik and Dincer [21]. During the experimental work, temperatures were measured hourly at various locations in the solar pond, at the bottom of pond and the insulated side-walls. The bottom and the side-walls of the pond were plated with the iron sheets of 0.005 m thickness, and in between with a glass wool of 50 mm thickness as the insulating layer. Exergy efficiencies of three zones of the solar ponds have been calculated and compared with the energy efficiencies on the basis of the energy and exergy model developed. The highest energy and exergy efficiencies are found to be: 4.22% and 3.02% for the UCZ, 13.80% and 12.64% for the NCZ, and 28.11% and 27.45% for the HSZ, respectively in the month of August under the climatic conditions of Cukurova University in Adana, Turkey as shown in Fig. 12.

It has been found that the exergy destruction and losses significantly affect the performance of the pond and should be minimized to increase the system efficiency. The distributions of exergy input, exergy stored, and exergy destruction and losses taking place in the HSZ during the eleven months of the year (except for June) are exhibited by a bar chart shown in Fig. 13. The exergy stored becomes smallest compared to the exergy inputs and exergy destruction and losses in the HSZ, and appears to be maximum in July as 743.10 MJ and minimum in January as 169.68 MJ, respectively. It is mentioned that the exergy destruction in the HSZ is caused by entropy generation directly which is a function of both entropy change within the system and entropy change in the surroundings due to the heat rejection.

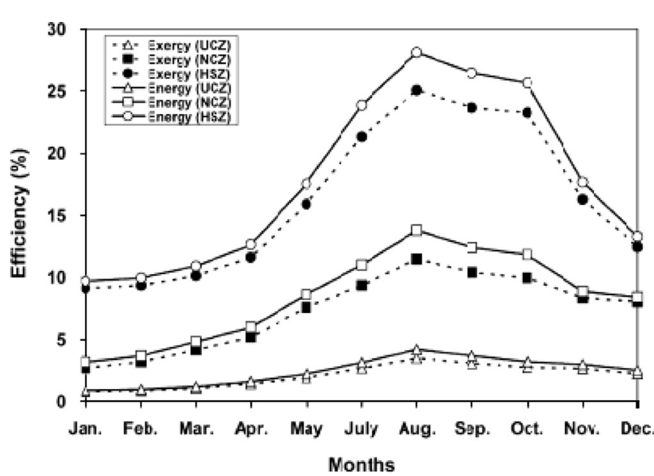

Fig. 12. Variations of the energy and exergy efficiencies of the three zones of the solar pond [21].

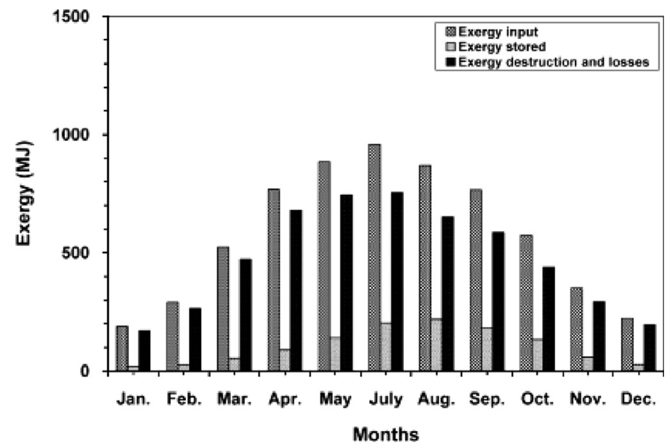

Fig. 13. Exergy distributions of exergy input, exergy stored, and exergy destruction and losses in the HSZ zone of the solar pond [21].

4. Theoretical and experimental studies of salt-gradient solar ponds for various applications

Numerous researchers have presented their findings of theoretical and experimental studies of SGSP technologies for various applications to ascertain its thermodynamic and economic feasibility. Comprehensive reviews of the recent studies having numerous references of the past research works are presented and compared in this section of the paper.

Solar ponds technologies offer good potential for collecting, storing and supplying of heat for different applications requiring low grade thermal energy. Thermal energy stored in the solar pond have been utilized for the better quality salt production by enhanced evaporation or purification of salt, aquaculture: using saline or fresh water to grow fish or brine shrimp, dairy industry to preheat feed water to boilers, fruit and vegetable canning industry, fruit and vegetable drying, grain industry for grain drying, production of drinking water through desalination process. The smaller ponds have been used mainly for space and water heating, swimming pool heating, while the larger ponds are proposed for industrial process heat, electric power generation, and sea water desalination on large scale [1–3,69].

This technology was used successfully at several remote sites in Australia in the 1970s. Low cost availability of other forms of energy, motivated people to discard the process of development of the solar ponds. Similar situations prevailed in the other parts of the world including some additional regional problems, where solar ponds were in use. Experts are trying to revive the solar pond technologies in the present circumstances. It has been emphasized that as a form of solar energy, the solar pond collector cum storage capacity has major advantages: the heat storage is massive, so energy can be extracted day and night – hence it is a source of 'base load' solar power – no batteries or other storage needed, it can have very large heat collection area at low cost. The major financially viable production potential is during peak electrical power demand in midsummer, when peak power price is high. The cost of power produced by a solar pond is about \$180/MW h i.e. about thrice that of wind (\$20–60/MWh in a windy area), four times that of coal fired power (\$40/MWh). Power from solar ponds is costly but more reliable delivering power 24 h a day and 365 days a year than power from wind energy. Like most solar energy systems, the running cost of solar pond power systems is negligible but the capital investment is considerably higher [70].

Kalogirou [71] has observed that there are several factors to be considered in evaluating a solar pond for a specific sites and applications. First, since solar ponds are horizontal solar collectors, sites should be at low to moderate northern and southern

latitudes, i.e. $\pm 40^{\circ}$. Another important consideration is that the water table should be at least a few meters below the bottom of the pond to minimize heat losses, since the thermal conductivity of soil increases greatly with moisture content. Also the pond must not pollute the aquifers and any continuous drain of hot water will lower the pond's storage capacity and effectiveness. The next item that must be considered is the selection of a liner for the pond. Although it is possible to build a soil liner by compacting clay, in some instances the permeability may be unacceptable. Resultant loss of fluid to the soil would increase thermal losses, require replenishment of salt and water, and may present an environmental problem. All ponds constructed today have contained a liner, which is a reinforced polymer material 0.75–1.25 mm in thickness. According to Dincer and Rosen [72], salinity-gradient solar ponds (SGSP) may be economically attractive in regions with little snow fall and areas where land is readily available.

4.1. Desalination and salt production

Renewable energy driven desalination systems' suitability are being investigated for practical applications. Solar assisted desalination has been proved technically feasible. It is reported by Li et al. [73] that the solar assisted desalination processes have not been commercialized up till now. With the current ongoing research; they remain a valid option for future desalination plants.

The solar pond-desalination system offers cost-effective solution for production of drinking water from brackish/saline water. Desalination by salt-gradient solar ponds has been studied in the US, Israel, and several other countries. The research at the E1Paso Solar Pond Project, El Paso, Texas in the period 1987–1992 mainly focused on the technical feasibility of thermal desalination coupled with solar ponds. Since 1999, the research has focused on long-term reliability, improvement of thermodynamic efficiency, and economics. During this period, a small multi-effect, multi-stage flash distillation (MEMS) unit, a membrane distillation unit, and a brine concentration and recovery system (BCRS) were tested over a broad range of operating conditions. The most important variables for the MEMS operation were flash range, concentration level of rejected brine, and circulation rate of the fast effect. The brine concentration and recovery system is part of the goal of developing a systems approach combining salinity-gradient solar pond technology with multiple process desalination and brine concentration. This systems approach, called zero discharge desalination, proposes concentrating brine reject streams down to near NaCI saturated solutions and using the solution to make additional solar ponds. In addition to presenting the test results on the MEMS and BCRS units, Lu et al. [74] also presented a summary of solar pond operation experiences obtained from the 16-year operation at the E1 Paso solar pond. Research at the El Paso solar pond has demonstrated that a salinity-gradient solar pond can be a reliable and environment friendly heating and cooling source for thermal desalination and brine concentration processes.

Kalogirou [71] has suggested the use of the output heat from salt-gradient solar pond to operate a low temperature distillation unit to desalt seawater. This concept has applicability in desert areas near the oceans. The implementation of the coupling of desalination technologies such as multi-stage flash (MSF), multiple-effect boiling (MEB), electrodialysis (ED) and reverse-osmosis (RO) with solar ponds is reported [70] citing the works of many researchers.

A simulation model describing the transient thermal behavior and economic analysis of a solar pond combined multi-stage desalination (MSF) system has been developed by Agha [75] under the conditions existing at Tripoli (Libya). Many conclusions drawn by this study confirm the utility of solar pond as the sole heat source (thermal energy) for distillation plant. Two years predictions of the heat storage zone temperature variations of this pond without heat extraction are plotted in Fig. 14. It is found that there is not much difference between the performance of the pond in the first and second year, which suggests that the temperature profiles for the following years may be almost the same as that for the second year. The highest and lowest temperatures of 105.54 °C and 65.67 °C are anticipated in the solar pond with the yearly average storage zone temperature of 85.61 °C, which is about 60 °C above the annual average ambient temperature. The yearly fluctuation of heat storage zone temperature is about 39.87 °C, which confirms that the pond can supply energy with a quantity that varies substantially with the season. Three cost estimates: capital cost (equipment purchase cost), energy cost (cost of thermal energy from solar pond and electric power cost to operate the circulation pumps) and operating and maintenance (O&M) cost have been considered during the economic analysis of the solar pond/MSF system. In this study, it is assumed that the construction of the pond, building the salt gradient zone, and heating the storage zone would take two years. The total life of the solar pond (which is mainly dependent on the liner) is assumed to be 30 years; the useful life is the estimated to be 28 years by subtracting the period of construction. The estimated cost of thermal energy from a solar pond as a function of heat storage zone temperature for different salt costs (assuming other parameters constant) is shown in Fig. 15. This diagram shows that the cost of thermal energy at an operating heat storage zone temperature of 70 °C is US$0.01380/kWh, $0.01813/kWh and $0.02246/kWh, respectively for three different assumed salt costs. The sensitivity analysis of the various factors affecting the overall water cost has been shown by plotting a number of diagrams. It is concluded that solar desalination is a capital intensive enterprise. Each 1% increase in interest rate increases solar pond thermal energy cost by about 13–15% and desalinated water cost from the solar pond/MSF system by about 10–13%. The changes in land cost have very little effect on the costs of thermal energy or the desalinated water costs [75].

A mini-solar pond can also be used for enhancing productivity of a solar still. Integration of a mini-solar pond with a solar still has been developed by Velmurugana and Srithar [76]. Various experiments for the yield of the distilled water from ordinary still, still with sponge, still integrated with a pond, and still with sponge

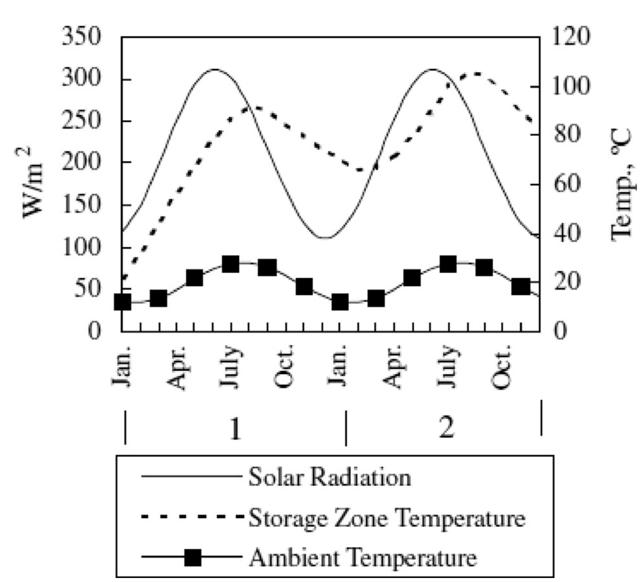

Fig. 14. Two years predictions of heat storage zone temperature variations for the solar pond, without heat removal [75].

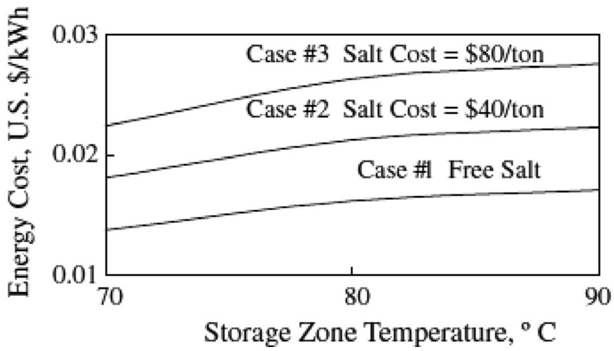

Fig. 15. Estimated cost of thermal energy from the solar pond viz. heat storage zone temperature [75].

integrated with mini-solar pond have been carried out. A solar still with sponge integrated with a mini-solar pond increases the distillate water production. The average distillate productivity of a mini-solar pond integrated with sponged still is 57.8% more than productivity of ordinary still.

It is worth to be mentioned here that the possibility of using solar ponds-as a source of low cost heat for desalination and salt production in the areas where fresh water is in short supply, but where brackish or sea-water is available had been explored by Tabor [77] also. A study conducted in 1975 showed that a solar pond of about 1/3 km^2 areas could operate a multi-effect distillation unit, commercially available, with an annual mean output of 4000 m^3 per day in a sunny climate. The cost of desalination (i.e. excluding the cost of the water) was computed at US$0.67/m^3 in 1975 of which the energy source i.e. the solar pond, represented one third and the distillation plant two thirds of the total capital cost. The solar pond which requires a source of salt or concentrated brine can also be used to produce salt from sea-water. The method, which requires pre-heating (and precipitation of sulfates) in conventional open-pan solar salt evaporating pans, uses a solar pond as a more efficient concentration mechanism. As a result, for a given ground area, the salt yield is about twice that for open-pan evaporation plants. (Because the precipitation takes place under controlled conditions in a crystalliser rather than in an open pond a high quality salt is obtained).

A largest solar pond constructed so far in Australia (Pyramid Salt's facility at Pyramid Hill in Victoria, Year: 2000–2002) having area of 3000 m^2 is providing heat for use in high grade salt production and aquaculture. The aim of this project was to make solar pond technology commercially available in Australia as an option for providing industrial process heat. It is estimated that solar ponds in climatic regions similar to northern Victoria can produce process heat (40–80 °C) for a wide range of applications at an average cost of about between $10 and $15/GJ. The results from the current project will provide actual data on cost of energy delivered, for the demonstration facility in next stages and commercially available systems [69].

An active solar distillation systems integrated with solar ponds are proposed and studied theoretically by Ranjan and Kaushik [78].With the integration of solar pond in the active solar still, the daily productivity, energy and exergy efficiency rises to about 9.5 L/m^2, 46% and 14.81% respectively, for thermal energy input variation from 100 W/m^2 to 500 W/m^2 during off-sunshine hours. The further improvement in the performance of the same system is observed if the thermal energy is supplied continuously (24 h) to the solar still in addition to incident solar radiation. The proposed and similar other systems are expected to meet the demand of freshwater in both rural and urban areas and help in reducing the load of CO_2 emission on the environment, saving high grade energy consumed for desalination through conventional devices and technologies. It is concluded that the active solar distillation systems integrated with solar ponds is one of the clean and green energy technologies which can be adopted for the conversion of saline/brackish/sea water into freshwater on low to medium scale for sustainable development.

4.2. *Domestic and industrial process heat*

The thermal processing used in the paper and food industries, heated water requirement in cooking, soaping, washing and other domestic uses, and process heat requirement of textile industries such as drying and dying of processed and finished cloths require low temperature heat. It can be supplied through solar ponds. The paper industry normally requires low pressure air or steam at about 200 °C for its processing. Solar ponds can be useful if they supplement energy requirement by preheating air before it goes to conventional type heaters. Styris et al. have estimated the size and cost of a pond which can be suitable to a typical processing plan [79].

4.3. *Agriculture and dairy plants*

Solar pond is suitable to supply heat for crop drying in which heated process air is used at about 38 °C in winter [79]. Murthy and Pandey [80] have studied the usage of solar pond for agriculture applications.

Technical and economic viability of solar pond technology in the Indian context was demonstrated by constructing and using a 6000 m^2 solar pond at Bhuj in India in the premises of a milk processing dairy plant by supplying process heat, as reported by Kumar and Kishore [81]. An inexpensive lining scheme, consisting of alternating layers of clay and LDPE (low density polyethylene) combination was used for lining the pond. The pond attained a maximum temperature of 99.88 °C under stagnation in May 1991 but developed leakage soon after. A failure analysis that was carried out subsequently indicated that the leakage was caused by the combination of high stagnation temperature and large air pockets below the liner. The lining scheme was re-designed and the pond re-established in June 1993. Hot water supply to the dairy started in September 1993 and continued until April 1995. After an interruption of nearly one year, hot water was resumed in August 1996. The total cost of construction of the Bhuj Solar Pond was US$90 000 (1997 prices), including heat exchanger and piping etc., corresponding to a unit cost of US$15 per m^2.

4.4. *Swimming pool heating*

Desired comfortable pool temperature for human beings is found to be in the range of 25–27 °C for spring and autumn and 24 °C for winter seasons. This low temperature requirement can be fulfilled by a heat source like solar pond. It has a potential of saving a large quantity of exergy from destruction due to use of fossil fuel based high grade energy like natural gas and electricity for the purpose of usual swimming pool heating in urban areas.

A 2000 m^2 pond was constructed at Miamisburg, Ohio, USA in 1978 for supplying heat to a municipal swimming pool. It supplies all of the heat needed for the pool during the swimming season and also supply heat to a bathhouse during other parts of the year [2].

4.5. *Space heating*

Applicability of solar ponds for space heating was perhaps investigated by Rabl and Nielsen [42] first time around 1974 in the United States. A solar pond for research in greenhouse heating was also constructed in 1975 at the Ohio Agricultural Research and Development Center, Wooster. Calculations indicated that in the

climate of Central Ohio a solar pond of sufficient depth will collect and store enough heat in summer to heat a house of the same area as the pond in the entire winter. The complete construction cost of a solar pond including the cost of heat removal system and excluding the maintenance cost was estimated to be US$ 37.50/m^2 (1974 price level) which was very much less than the cost of conventional roof type solar heating systems. By the comprehensive study, it was concluded that solar ponds may be competitive with conventional heating of space.

An expression for determining a single set of solar pond dimensions for a given heating requirement was derived by Styris et al. [79] and applied to hypothetical pond. Solar pond dimensions were determined for house heating, winter crop drying and paper processing. Tabor [77] has also proved the utility of solar ponds for heating and cooling of buildings by reporting the findings of many investigators.

The requirement for direct winter heating of greenhouses necessitates a pond at a temperature above 40 °C. This temperature is difficult to maintain in a solar pond because of heat losses from the heat storage zone and the reduction in available solar radiation during winter. It has been found that by introducing a heat pump, which can operate efficiently between 5 and 40 °C, it is possible to operate the pond over an extended period. Shah et al. [82] have provided several significant results about the operating characteristics of a solar pond assisted heat pump system and the performance of individual components through computer simulation analysis. It was concluded that the surface area and depth of the solar pond are two very important design variables. The heat pump can greatly increase the effectiveness of a solar pond that is attached to a heating load requiring temperatures above 40 °C. The NCZ depth is found to be very critical and a pond having NCZ depth of 1.0 m gave a better coefficient of performance (COP) and delivered 20 % more heat to the greenhouse as compared to the 1.5 m depth of NCZ. Taga et al. [83] have also reported that heating requirement of a greenhouse can be fulfilled by the hot water stored in the solar pond using a gas engine powered heat pump.

4.6. Refrigeration and air-conditioning

Demand of refrigeration and air-conditioning is much in summer, when there is much availability of solar energy. Cooling from heat of the solar energy is one of the most interesting applications of solar thermal technologies developed to date. Requirement of low grade thermal energy in the absorption and adsorption refrigeration cycle can be supplied by a solar pond. There are a few instances of utilization of solar ponds for refrigeration and air-conditioning mentioned elsewhere in literature.

4.7. Power generation

The need of electricity production through solar power generation system has been felt worldwide. The cost of the heat collecting elements (either flat plates, or parabolic troughs or dish mirrors or heliostats) and their influence upon the cost of electricity produced in a solar power plant is a real hindrance in the introduction of solar energy into wider use. A relatively simple and inexpensive solution was thought to be the Solar Pond even in 1960s as envisaged by Tabor [40]. It is the most promising and viable option for supplying heat at temperature of about 100 °C to low temperature solar thermal power plants working on Organic Rankine Cycle (ORC). The working fluid of low boiling points: methyl chloride and toluene, and refrigerants like R-11, R-113 and R-114 are normally used in the Rankine cycle. The first two solar pond power plants having capacities of 6 kW and 150 kW were constructed in Israel about 30 years ago. A solar pond plant consisting of 5 MW ORC turbine and the pond of 2,50,000 m^2 area generated 800 kW electricity from 1983 to 1990 at Beit Ha'aravah near the northern shores of the Dead Sea on a continuous basis [84]. However, thermodynamic efficiency of such a low-temperature power-producing system was found to be low. The working of these plants firmly established the technical viability of solar pond power plants. Economically, it was not attractive in spite of being less costly than plants using flat-plate collector systems [1,84].

In recent times, the concept of combining a chimney with a salt-gradient solar pond for generation of power is being studied. Akbarzadeh et al. [85] have examined it and found that such an integration incorporating an air turbine for the production of power is possible with the potential benefit of being able to generate power intermittently at any time (day or night) and at times of peak demand (or high cost for electricity). It would also be possible to operate the power generation unit continuously as a provider of base load energy. Such flexibility results from the inherent heat storage capabilities of a solar pond. It is shown that for the conditions in northern Victoria (19 MJ/m^2 day annual solar radiations) 60 kW of power can be generated for the case where air in the chimney has been heated from an initial condition of 20 °C to 50 °C. This value is increased to 90 kW when the air is heated to 60 °C. It is estimated that the 60,000 m^2 solar pond in this model can produce 78840 GJ of thermal energy annually (assuming an efficiency of 20% for conversion of solar to thermal energy) having a temperature between 50 and 75 °C and will ideally produce approximately 90,000 kWh of electrical energy per year (considering a chimney of 200 m height and a diameter of 10 m resulting in a conversion efficiency of approximately 0.4% for thermal to mechanical energy).On a continuous basis the electrical power output is estimated to be 6 kW in winter and 15 kW in summer. However, for intermittent operation (few hours up to few days) heat can be extracted from the pond at a rate of 60 MW producing 250 kW of electrical power. The estimated powers can be expected to increase by incorporating a taller tower.

Generation of electricity from large solar ponds has been successfully demonstrated. There is negligible evidence of practical and viable proposal of power generation from small scale solar ponds. A solar pond of a few hundred square meters may be able to produce enough heat that after conversion can satisfy the electricity demand for an energy-efficient house (say 2–5 kWh/day). Construction and maintenance of a solar pond of this size is not a problem but the conversion of thermal energy to power is a difficult challenge. Conventional heat engines have too many moving parts and are complex. They are very expensive (15,000–20,000 $/kW) in these small sizes (less than 0.5 kW) and difficult to maintain. Applications of thermoelectric concepts with solar ponds have great potential to mitigate these problems. In solar ponds, temperature difference in the range 40–60 °C is available between the lower convective zone (LCZ) and the upper convective zone (UCZ) which can be applied across the hot and cold surfaces of the thermoelectric modules to make it work as a power generator. A system designed by Singh et al. [86] utilizes gravity assisted thermosyphon to transfer heat from the hot bottom to the cold top of the solar pond. Thermoelectric cells (TECs) are attached to the top end of the thermosyphon which lies in the UCZ thereby maintaining differential temperature across them. A laboratory scale model based on the proposed combination of thermosyphon and thermoelectric cells was fabricated and tested under the temperature differences that exist in the solar ponds.

The potential of thermoelectric generators as a power generation system using heat from the salt-gradient solar pond is investigated by Singh et al. [87]. It is found that these systems may be capable of producing electricity from low grade heat source particularly for power supply in remote areas even on

cloudy days or at night because of the thermal storage capability of the solar pond.

5. Conclusions and recommendations

This paper reviewed the state-of-the-art in the field of solar pond technologies, its thermodynamic and economic feasibility. It has been found that thermal energy from solar ponds can be useful to various applications requiring low grade energy. In this paper, review of different methods of extraction of heat to enhance the effectiveness of the solar ponds, results of experimental and theoretical studies, study about integration of solar ponds with other solar and non-solar systems like thermoelectric generator, solar chimney, desalination devices, etc. are also presented.

There are a number of thermodynamic models developed and validated with the experimental results by researchers worldwide for the performance analysis of solar ponds through energy analysis. A few studies are also carried out recently with an effective thermodynamic tool based on the second law of thermodynamics, i.e. exergy analysis. Exergy analysis of solar ponds has been found complementary to energy analysis.

It is observed that temperature in HSZ of a typical SGSP can reach about 100 °C. The zone-wise and overall energy efficiency of solar pond depends mainly on design and climatic conditions, and methods of heat extraction. Shading effects of the side wall on the collection efficiency is negligible for larger solar ponds. But collection efficiency reduces significantly with the increase of turbidity. The heat extraction from the NCZ as well as HSZ may increase the overall energy efficiency of the solar pond by up to 55% without affecting the density profile. Integration of solar ponds with flat-plate collectors, solar distillation system and other solar thermal systems increases its utility to a greater extent and found to be an active area for future research and innovation. Combination of thermosyphon and thermoelectric generators as a power generation system using heat from the SGSP promises great hope for electricity production from low grade heat source.

Result of studies done by researchers′ shows that the exergy efficiencies are lower than the energy efficiencies of each zone of the solar pond. It is mainly due to exergy destructions in the zones and losses to the environment. Therefore, the true magnitudes, causes and location of exergy destructions and losses are to be ascertained. Then appropriate measures are to be taken to minimize the exergy destruction and losses for the performance improvement of the solar pond systems economically.

Solar pond technology is technically feasible to all such applications but for a specific use, a larger separate solar pond may not be economically feasible due to higher cost involved and large land area requirement. Large solar pond may be planned for multi-applications fulfilling the need of heating buildings of a housing society, process industries, electricity generation, etc. as it has capacity of storing huge amount of thermal energy for longer periods. Even in the fossil fuel based thermal power plant, a large amount of heat is required to preheat the feed-water up to saturation temperature in the boiler and air-preheating which may be done by the use of solar pond in addition to fulfilling the heating and cooling need of the township of thermal power stations. Development and use of mini-solar ponds have been found thermodynamically and economically feasible.

It is concluded that there is immense scope of systematic research in the field of technology development to use thermal energy from solar ponds for refrigeration and air-conditioning, process heating, desalination, and many other applications in which fossil fuel based energy is consumed extensively. Authors are in view that there is an opportunity to develop and commercialize an environment friendly new technology based on solar pond to meet the demand of energy and water of the large population of the world particularly in the third world living in rural and remote areas where there is less or no supply of electricity.

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